

# Distribution of light and heavy fractions of soil organic carbon as related to land use and tillage practice

Z. Tan<sup>a,\*</sup>, R. Lal<sup>a</sup>, L. Owens<sup>b</sup>, R.C. Izaurralde<sup>c</sup>

<sup>a</sup> Carbon Management and Sequestration Center, The Ohio State University,  
2021 Coffey Road, Columbus, OH 43210, USA

<sup>b</sup> USDA-ARS, North Appalachian Experimental Watersheds, Coshocton, OH 43812, USA

<sup>c</sup> Joint Global Change Research Institute, 8400 Baltimore Ave., Suite 201, College Park, MD 20740, USA

Received 14 October 2004; received in revised form 18 January 2006; accepted 23 January 2006

## Abstract

Mass distributions of different soil organic carbon (SOC) fractions are influenced by land use and management. Concentrations of C and N in light- and heavy fractions of bulk soils and aggregates in 0–20 cm were determined to evaluate the role of aggregation in SOC sequestration under conventional tillage (CT), no-till (NT), and forest treatments. Light- and heavy fractions of SOC were separated using 1.85 g mL<sup>-1</sup> sodium polytungstate solution. Soils under forest and NT preserved, respectively, 167% and 94% more light fraction than those under CT. The mass of light fraction decreased with an increase in soil depth, but significantly increased with an increase in aggregate size. C concentrations of light fraction in all aggregate classes were significantly higher under NT and forest than under CT. C concentrations in heavy fraction averaged 20, 10, and 8 g kg<sup>-1</sup> under forest, NT, and CT, respectively. Of the total SOC pool, heavy fraction C accounted for 76% in CT soils and 63% in forest and NT soils. These data suggest that there is a greater protection of SOC by aggregates in the light fraction of minimally disturbed soils than that of disturbed soil, and the SOC loss following conversion from forest to agriculture is attributed to reduction in C concentrations in both heavy and light fractions. In contrast, the SOC gain upon conversion from CT to NT is primarily attributed to an increase in C concentration in the light fraction.

© 2006 Elsevier B.V. All rights reserved.

**Keywords:** Conventional tillage; Density fractionation; Heavy fraction; Light fraction; No-till; Soil organic carbon

## 1. Introduction

Changes in total soil organic carbon (SOC) with change in land use and management can be partly explained by the way C is allocated in different fractions of soil organic matter (SOM). These fractions exhibit different rates of biochemical and microbial degradation (Stevenson, 1994) as well as different accessibility

and interactions (Sollins et al., 1996). The dynamics of SOC is usually described by dividing SOM into two or more fractions. Physical fractionation of SOM is useful for distinguishing specific C pools responsive to management, identifying the physical control of SOM (Cambardella and Elliott, 1993a; Collins et al., 1997), and characterizing the relationship between SOM and size distribution of aggregates (Feller et al., 1996). Density fractionation is a laboratory procedure that physically separates soil into light- and heavy fractions (Wander and Traina, 1996; Sollins et al., 1999). The procedure is useful for assessing labile pools of SOM that are more sensitive to cropping practice than is the total SOC pool in temperate soils (Janzen

\* Corresponding author at: Science Applications International Corporation, Contractor to the USGS/EROS, 47914 252nd St., Sioux Falls, SD, USA. Tel.: +1 605 594 6903; fax: +1 605 594 6529.

E-mail address: [ztan@usgs.gov](mailto:ztan@usgs.gov) (Z. Tan).

et al., 1992). Among liquids for density fractionation, sodium polytungstate (SPT) solution at  $1.85 \text{ g mL}^{-1}$  is often used (Magid et al., 1996; Six et al., 1998, 2002).

Light fraction is commonly referred to a plant-like and less stable fraction with high C concentration (Golchin et al., 1994; Gregorich et al., 1996). Heavy fraction is a more stable and high-density organo-mineral fraction having lower C concentrations (Golchin et al., 1995a, b). Light fraction of SOM is not only sensitive to changes in management practices (Cambardella and Elliott, 1992; Bremer et al., 1994) but also correlates well with the rate of N mineralization (Hassink, 1995; Barrios et al., 1996). By incubating bulk soil and density fractions, Alvarez et al. (1998) and Alvarez and Alvarez (2000) observed that light fraction C was the driving factor in soil respiration. Light fraction supposedly represents an intermediate pool between undecomposed residues and humified SOM (Gregorich and Janzen, 1996). In contrast, heavy fraction contains more processed SOM (Hassink, 1995; Wander and Traina, 1996) and can be a major sink for C storage in soil because it has little mineralizable C (Barrios et al., 1996; Whalen et al., 2000) as is demonstrated by poor relationship with soil respiration (Alvarez and Alvarez, 2000). The importance of light fraction (including free and occluded organic C within aggregates) is widely recognized for its role in the formation and stability of soil structure, especially in the stabilization of soil macroaggregates ( $>250 \mu\text{m}$ ) (Miller and Jastrow, 1990; Kay, 1998). Janzen et al. (1992) reported that light fraction of surface soil (0–7.5 cm) accounted for 2–17% of the SOC, depending largely on cropping systems. However, there are few direct data quantifying these two fractions and their contributions to total SOC storage as related to changes in land use and tillage practices. Therefore, this study was conducted to assess the effects of land use and tillage practices on SOC sequestration by quantifying mass distribution of light- and heavy fractions and their relationships to aggregate size classes under forest, no-till (NT), and conventional tillage (CT) treatments.

## 2. Materials and methods

### 2.1. Site description

Soil samples for this study were obtained from research sites located at the North Appalachian Experimental Watershed (NAEW, USDA-ARS), near Coshocton, Ohio, USA ( $40^{\circ}24'\text{N}$ ;  $81^{\circ}48'\text{W}$ ). The altitude ranges from 244 to 381 m, the mean annual temperature is  $10.5^{\circ}\text{C}$ , and the mean annual precipitation is 958 mm. Predominant soil series at this site include Berks (loamy-skeletal, mixed, mesic, Typic Dystrochrepts), Coshocton (fine-loamy, mixed, mesic Aquultic Hapludalfs), and Rayne (fine-loamy, mixed, mesic, Typic Hapludalfs) (Kelley et al., 1975). These soils are dominated by silt (about 65%) and contain only 13–19% clay. Soil samples were taken from three watersheds under: (1) secondary growth forest (since the early 1930s) consisting of white oak (*Quercus alba* L.), red oak (*Quercus rubra* L.), and yellow poplar (*Liriodendron tuliperifera*), (2) NT continuous corn (*Zea mays* L.), and (3) CT continuous corn. Some properties of these soils are listed in Table 1.

### 2.2. Soil sampling and treatments

Soil samples were collected in November 2001 (after corn harvest) from mid-slope and down-slope landscape positions in each watershed. The summit position was excluded to minimize the confounding effect of soil erosion. Undisturbed soil cores (5 cm diameter and 5 cm long) were taken in triplicate at 0–5, 5–10, and 10–20 cm depths for bulk density ( $\rho_b$ ) determination. Soil samples for C and N determinations were taken using a soil probe (2.5 cm diameter) at the same depth intervals as those for  $\rho_b$  determination. The sample for each depth interval was composed of about 20 soil cores randomly collected across each watershed, by which all soil samples for each depth interval were collected in triplicate.

The  $\rho_b$  was determined using the method proposed by Blake and Hartge (1986). All composite samples

Table 1  
Background information of experimental plots and soils

Treatment	Soil series	Vegetation/ cropping	Depth (cm)	Texture	Bulk density ( $\text{mg m}^{-3}$ )	Clay ( $\text{g kg}^{-1}$ )	Silt ( $\text{g kg}^{-1}$ )	SOC ( $\text{g kg}^{-1}$ )	CEC $\text{cmol kg}^{-1}$
CT (since 1984)	Berks silt loam	Continuous corn	0–23	Silt loam	1.47	136	634	14.0	10.1
NT (since 1974)	Rayne silt loam	Continuous corn	0–18	Silt loam	1.46	164	604	13.0	12.1
Forest (since 1938)	Coshocton silt loam	Red and white oak	0–25	Silt loam	1.34	161	674	17.5	12.1

Source: Kelley et al. (1975).

were gently broken apart by hand and passed through a 6.75 mm sieve while still at field moisture content, and then air-dried. Soil moisture contents of sub-samples were determined by drying at 105 °C for 24 h. Soil pH (1:2.5 soil–water ratio) ranged from 7.1 in the agricultural soils to 4.6 in the forest soil. There was no indication of the presence of carbonates.

### 2.3. Water stable aggregate fractionation

A 30 g sample of air-dried bulk soil (passing a 6.75 mm sieve) was placed on the top of a set of nested sieves (2000, 250, and 53  $\mu\text{m}$ ) (Elliott, 1986). Samples were slaked with DI-water for 30 min at 25 °C (Kemper and Rosenau, 1986). The nested sieves were gently oscillated (5 cm amplitude of 25 strokes  $\text{min}^{-1}$ ) within a column of water for 30 min. Floating free particulate organic matter (POM) was removed during the wet sieving and not included in the analysis. Aggregate fractions were then recovered and dried at 60 °C to constant moisture contents.

### 2.4. Density fractionation

For density fractionation and determination of total C and N concentrations, bulk soil samples and aggregates  $>250 \mu\text{m}$  were ground using an 8000 SPEX CertiPrep Mixer/Mill (Spex CertiPrep Inc., Metuchen, NJ) at a moderate speed to prevent breakdown of gravel and passed through a 250  $\mu\text{m}$  sieve. Materials retained on the sieve were discarded. About 2.0 g dried sample (either bulk soil or aggregates) was transferred to a 50 mL graduated centrifuge tube, and dispersed in 20 mL of 0.5% sodium hexametaphosphate. The suspension was shaken for 18 h on a horizontal shaker (Eberback, 115 volts-60 CY, Ann Arbor, MI). After washing with 5 mL deionized water, 66 g of SPT powder ( $2.89 \text{ g cm}^{-3}$ ) was added to the centrifuge tube to make a solution with a density of  $1.85 \text{ g SPT mL}^{-1}$  (total suspension volume, including soil particles, was brought to 36.0 mL). The tube was shaken thoroughly for 10 min. After overnight standing, the tube was gently tilted to remove heavy particles from the upper wall of the tube. The suspension was centrifuged at 1250 g for 60 min (Elliott and Cambardella, 1991; Cambardella and Elliott, 1993b). The supernatant (or light fraction) was collected using a 20  $\mu\text{m}$  nylon filter and washed, then transferred to an aluminum pan (4 cm in diameter) and dried at 60 °C for future use. Meanwhile, the heavy fraction remaining in the centrifuge tube was washed three times with 40 mL

DI-water by centrifuging at 1250 g for 30 min. Finally, the residue (or heavy fraction) was dried at 60 °C overnight, weighed for light fraction mass proportion calculation, and ground to pass a 250  $\mu\text{m}$  sieve for C and N determinations.

### 2.5. Carbon and nitrogen determination and data analysis

Bulk soil, aggregates, and heavy fractions were analyzed for C and N by the dry combustion method (900 °C) using a CN analyzer (Vario Max CN Analyzer, Elementar Americas, Inc., NJ). Light fraction C and N were determined from the difference between total and heavy fraction C and N.

The SAS software (SAS Institute and Inc., 2002) was used for statistical analysis. Land use and management practices (i.e. treatments) were considered as a main effect for the same sampling depth, and replications were treated as a random effect. A two-way ANOVA with depth and treatment as main effects was performed to calculate the Fisher's LSD (least significant difference). A general linear model was used to assess treatment effects on soil C and N concentrations, C:N ratio, and C and N of both light- and heavy fractions. Significance was determined at  $\alpha = 0.05$  from each treatment and depth separately.

## 3. Results and discussion

### 3.1. Light and heavy fractions in bulk soil

#### 3.1.1. Mass proportions of light- and heavy fractions in bulk soil

Characteristics of bulk soil and density fractions associated with sampling depths are listed in Table 2. Across soil depths, significant difference ( $p < 0.05$ ) was observed among treatments with respect to SOC concentration (forest  $>$  NT  $>$  CT). The light fraction accounted for 12.0%, 10.8% and 5.7% of the total soil mass in forest, NT and CT soils, respectively. Averaged across all treatments, light fraction decreased with depth from 11% in the 0–5 cm to 8.8% in the 10–20 cm depth. In the forest and NT soils, both the bulk SOC and the mass portion of light fraction gradually decreased with depth. In the CT soil, however, variation with depth was minor probably due to homogenization and mixing effect of plowing. A higher mass proportion of light fraction was observed in this study than reported by Wander and Traina (1996), which may be due to greater light fraction recovery resulting from the use of a higher density SPT solution ( $1.85 \text{ g mL}^{-1}$  versus  $1.65 \text{ g mL}^{-1}$ ).

Table 2

Characteristic summary of density fractions of soil organic matter

Depth (cm)	Treat.	Bulk density ( $\text{mg m}^{-3}$ )	Bulk soil ( $\text{g kg}^{-1}$ )		LF/BS (%) <sup>a</sup>	LF ( $\text{g kg}^{-1}$ LF) <sup>b</sup>		HF ( $\text{g kg}^{-1}$ HF) <sup>c</sup>	
			SOC	SON		LFC	LFN	HFC	HFN
0–5	CT	1.49 b	9.4 (0.2) e	0.9 (0.1) e	5.6 (0.9) e	41.0 e	1.5 ef	7.5 (0.1) d	0.9 (0.0) cd
	NT	1.37 c	28.3 (0.5) b	2.4 (0.1) b	12.9 (0.3) ab	88.0 b	4.9 c	19.4 (1.0) b	2.0 (0.0) b
	Forest	1.05e	45.8 (2.1) a	3.3 (0.1) a	14.4 (0.3) a	147.4 a	6.6 a	28.6 (0.1) a	2.8 (0.1) a
5–10	CT	1.69 a	9.4 (0.4) e	1.0 (0.0) e	5.9 (0.1) e	36.2 e	1.0 f	7.8 (0.3) d	1.0 (0.0) cd
	NT	1.64 ab	11.9 (0.7) d	1.2 (0.1) de	11.0 (0.1) c	41.4 e	2.2 ef	8.3 (0.0) d	1.1 (0.0) cd
	Forest	1.26 d	25.6 (1.3) b	2.2 (0.1) b	11.7 (0.2) bc	60.4 d	3.3 d	21.0 (0.6) b	2.0 (0.0) b
10–20	CT	1.74 a	10.3 (0.1) de	1.0 (0.0) e	5.7 (0.0) e	45.9 e	1.6 ef	8.2 (0.1) d	1.0 (0.0) cd
	NT	1.74 a	7.5 (0.5) f	0.9 (0.1) e	9.7 (0.2) d	23.4 f	1.0 f	5.8 (0.4) e	0.8 (0.1) d
	Forest	1.55 b	21.8 (1.6) c	2.0 (0.0) bc	10.9 (0.1) cd	69.9 cd	5.2 b	15.9 (0.2) c	1.6 (0.0) bc
0–20 <sup>d</sup>	CT	1.67 A	9.9 (0.4) C	1.0 (0.1) B	5.7 (0.2) C	42.2 B	1.4 B	7.9 (0.2) B	1.0 (0.1) B
	NT	1.62 A	13.8 (1.1) B	1.3 (0.1) B	10.8 (0.6) B	44.1 B	2.3 B	9.8 (0.4) B	1.2 (0.1) B
	Forest	1.35 B	28.8 (1.7) A	2.4 (0.2) A	12.0 (0.5) A	86.9 A	5.1 A	20.4 (0.6) A	2.0 (0.2) A

Note: Means within a column and depth group followed by the same letter are not significantly different at  $p < 0.05$  using Fisher's LSD; values in parentheses are standard deviations of the means.

<sup>a</sup> Weight percentage of light fraction (LF) mass in bulk soil (BS).

<sup>b</sup> The mass of light fraction C (LFC) or N (LFN) divided by the mass of all light fraction SOM.

<sup>c</sup> The mass of heavy fraction C (HFC) or N (HFN) divided by all heavy fraction mass including soil minerals.

<sup>d</sup> Weighted by sampling depth.

### 3.1.2. Carbon and nitrogen concentrations

Significant treatment effects ( $p < 0.05$ ) were also observed on C and N concentrations in both light and heavy fractions (Table 2). The C concentration in heavy fraction decreased sharply with sampling depth from  $18.5 \text{ g C kg}^{-1}$  in the first depth interval to  $10.0 \text{ g C kg}^{-1}$  in the third depth interval. Averaged across sampling depths, the highest C concentrations in both light- and heavy fractions were observed in soil under forest, with no difference between NT and CT treatments. A similar trend (but much smaller magnitudes) was also observed for N concentrations.

The C:N ratio of the heavy fraction (average 8.8) was consistently smaller than that of the light fraction (average 22.1), regardless of treatments and sampling

depths (Fig. 1). However, the light fraction showed a greater variation in the C:N ratio with treatment and depth (range 13.4–36.2), revealing its response to change in soil management.

### 3.2. Light- and heavy fraction C and contribution to SOC pool

The SOC stock ( $\text{kg C m}^{-2}$ ) in 0–20 cm depth of soil differed significantly among treatments. Soils under NT and forest had 94% and 242% more light fraction C than did CT soils, respectively (Fig. 2A). A similar trend was observed for the light fraction N (Fig. 2B). The pool of heavy fraction C dominated total SOC: 76% under CT, 63% under NT and forest (Fig. 2A). The contribution of

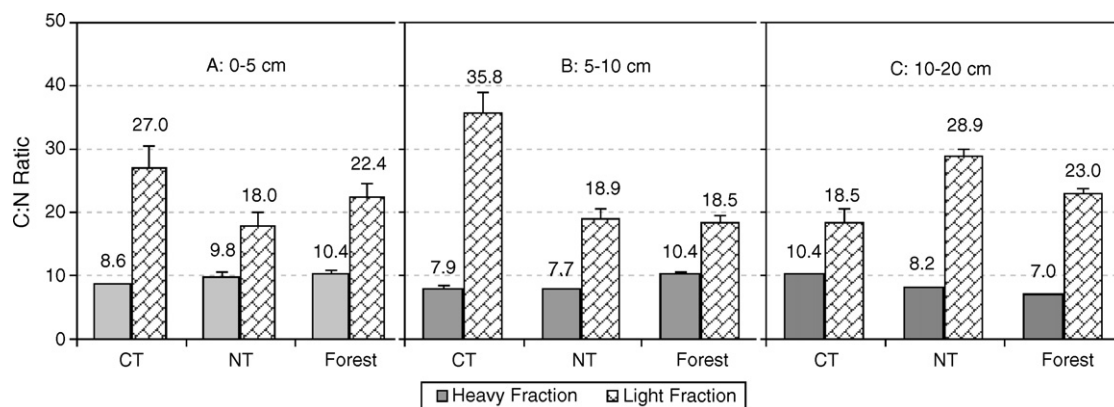


Fig. 1. C:N ratios of light fraction (LF) and heavy fraction (HF) in bulk soils for each sampling depth interval (LSD = 2.4,  $\alpha = 0.05$ ).

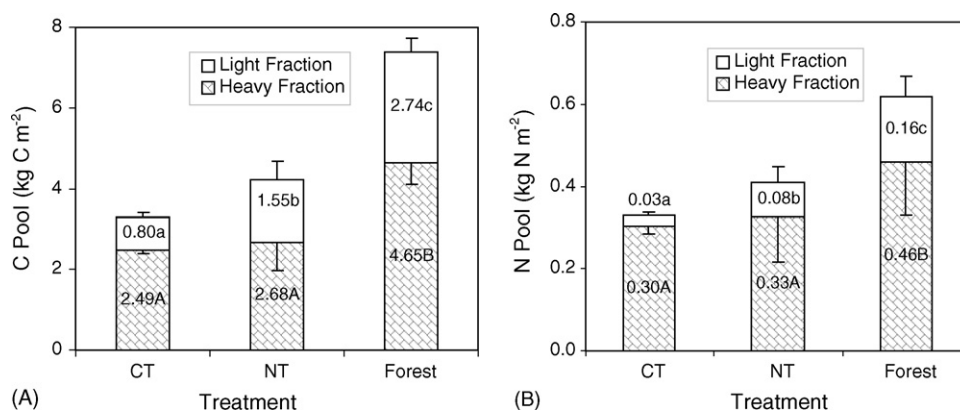


Fig. 2. Fraction C and N pools in 0–20 cm depth of soils; the same letters in a column mean no significant difference at  $p < 0.05$ .

heavy fraction C pool to total SOC pool under CT (as well as heavy fraction N) was significantly higher than that under NT and forest. The pool of heavy fraction C was also differentiated by treatment:  $4.65 \text{ kg m}^{-2}$  for forest,  $2.68 \text{ kg m}^{-2}$  for NT, and  $2.49 \text{ kg m}^{-2}$  for CT (Fig. 2A), implying a 45% loss of heavy fraction C since the change from forest to agriculture. The data presented here indicate that the C loss following conversion from forest to agriculture was due to a reduction in both heavy- and light-fraction C, while the C gain with conversion from CT to NT was principally attributed to light fraction C.

### 3.3. Characteristics of density fractions associated with aggregates

Table 3 shows that the mass proportions of three aggregate size classes in 0–5 cm depth varied sig-

nificantly with treatments. In comparison with soils under NT and forest, the soil under CT was dominated by 53–250  $\mu\text{m}$  aggregates followed by the 250–2000 and  $>2000 \mu\text{m}$  class sizes. Meanwhile, the quantities of light fraction occluded in different size classes of aggregates were significantly smaller under CT than under NT and forest (Table 3). The mass portion of light-fraction associated with aggregates  $>2000 \mu\text{m}$  class and relevant data under CT treatment was not reported because the amount of aggregates  $>2000 \mu\text{m}$  was too small for performing analyses. The mass portion of light fraction occluded in aggregates 250–2000  $\mu\text{m}$  under CT was only 61% of that under NT or Forest. The mass distribution of light fraction associated with each aggregate class and variations with tillage treatments presented in Table 3 are in accord with results reported by other researchers (Oades and Waters,

Table 3

Characteristic summary for different density fractions associated with aggregates in the top 5 cm depth

Treat	Agg. size ( $\mu\text{m}$ )	Agg. mass (%)	Bulk soil ( $\text{g kg}^{-1}$ )		LF/BS (%) <sup>a</sup>	LF ( $\text{g kg}^{-1}$ ) <sup>b</sup>		HF ( $\text{g kg}^{-1}$ ) <sup>c</sup>		Contribution % <sup>d</sup>	
			SOC	SON		LFC	LFN	HFC	HFN	HFC	HFN
CT	$>2000$	6.8 f	10.6 f	1.1 c		Not available due to limited sample					
	250–2000	17.2 e	11.9 f	1.2 bc	5.4 ef	95 f	8.5 b	7.2 d	0.8 c	57 c	63 cd
	53–250	42.9 b	7.8 f	1.0 c	4.7 f	46 g	6.0 c	5.9 d	0.7 c	72 a	71 c
NT	$>2000$	16.4 e	30.9 cd	1.8 ab	9.7 ab	192 e	6.4 c	13.6 b	1.3 b	40 d	66 cd
	250–2000	39.6 b	30.5 cd	1.7 b	8.7 bc	204 e	3.4 e	13.9 b	1.4 b	42 d	82 b
	53–250	26.5 d	21.1 e	1.6 b	7.3 d	106 f	4.5 d	14.4 b	1.4 b	64 b	80 b
Forest	$>2000$	18.9 de	49.9 a	2.2 a	10.4 a	388 a	9.7 a	10.9 c	1.3 b	19 f	53 e
	250–2000	50.2 a	42.0 b	2.1 a	8.8 bc	346 ab	8.8 b	12.8 bc	1.4 b	28 e	63 cd
	53–250	19.3 de	37.4 bc	2.2 a	7.2 d	184 e	2.3 f	26.0 a	2.2 a	65 ab	93 a

Note: Means within a column and treatment group followed by the same letter are not significantly different at  $p < 0.05$  using Fisher's LSD; values in parentheses are standard deviations of the means.

<sup>a</sup> Weight percentage of light fraction (LF) mass in bulk soil (BS).

<sup>b</sup> The mass of light fraction C (LFC) or N (LFN) divided by the mass of all light fraction SOM.

<sup>c</sup> The mass of heavy fraction C (HFC) or N (HFN) divided by all heavy fraction mass including soil minerals.

<sup>d</sup> The contribution of the HFC to SOC and that of the HFN to SON.



1991; Gregorich et al., 1996; Gale et al., 2000). The C and N concentrations in aggregate size classes of 53–250 and 250–2000  $\mu\text{m}$  under CT were substantially lower than those under NT and forest. Generally, the mass portion, C concentration, and C:N ratios of light fraction increased with increase in aggregate size. These data support the hypothesis that macroaggregates ( $>250 \mu\text{m}$ ) protect recently deposited particulate C with high C:N ratios (Cambardella and Elliott, 1993a; Golchin et al., 1995b; Jastrow, 1996; Six et al., 1998). Lower quantities of LF in CT than NT or forest sites in macroaggregate size classes suggest that tillage destroys these aggregates, in particular, and releases protected LF that is subsequently oxidized. Conversely, the heavy fraction C of 53–250  $\mu\text{m}$  aggregates made a larger contribution to total SOC than did  $>250 \mu\text{m}$  aggregates. Compared with NT (and forest), the soil under CT contained a higher portion of heavy fraction C in respective aggregate classes. This implied a weaker physical protection of light fraction under CT versus NT due to soil disturbance by tillage.

#### 4. Conclusions

The data presented supports the following conclusions:

- (1) heavy fraction C and N determined total C and N in these soils, and
- (2) the SOC loss caused by conversion from forest to agricultural land use could be attributed to reduction in both heavy- and light-fractions, while the SOC gain following conversion from CT to NT could be attributed to C increase in the light fraction only.

#### Acknowledgements

This research was funded by the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGs). The authors highly appreciate several anonymous reviewers for their thoughtful comments.

#### References

- Alvarez, R., Alvarez, C.R., 2000. Soil organic matter pools and their associations with carbon mineralization kinetics. *Soil Sci. Soc. Am. J.* 64, 184–189.
- Alvarez, C.R., Alvarez, R., Grigera, M.S., Lavado, R.S., 1998. Associations between organic matter fractions and the active soil microbial biomass. *Soil Biol. Biochem.* 30, 767–773.
- Barrios, E., Buresh, R.J., Sprent, J.I., 1996. Nitrogen mineralization in density fractions of soil organic matter from maize and legume cropping systems. *Soil Biol. Biochem.* 28, 1459–1465.
- Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods*. Soil Science Society of America, Madison, WI, pp. 325–340.
- Bremer, E., Jansen, H.H., Johnston, A.M., 1994. Sensitivity of total, light fraction and mineralizable organic matter to management practices in a Lethbridge soil. *Can. J. Soil Sci.* 74, 131–138.
- Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic matter changes across a grassland sequence. *Soil Sci. Soc. Am. J.* 56, 777–783.
- Cambardella, C.A., Elliott, E.T., 1993a. Carbon and nitrogen mineralization in aggregates from cultivated and native grassland soils. *Soil Sci. Soc. Am. J.* 57, 1071–1076.
- Cambardella, C.A., Elliott, E.T., 1993b. Methods for physical separation and characterization of soil organic matter fractions. *Geoderma* 56, 449–457.
- Collins, H.P., Paul, E.A., Paustian, K., Elliott, E.T., 1997. Characterization of soil organic carbon relative to its stability and turnover. In: Paul, E.A., Elliott, E.T., Paustian, K., Cole, C.V. (Eds.), *Soil Organic Matter in Temperate Agroecosystems, Long-term Experiments in North America*. CRC Press, Boca Raton, FL, pp. 51–72.
- Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Sci. Soc. Am. J.* 50, 518–524.
- Elliott, E.T., Cambardella, C.A., 1991. Physical separation of soil organic matter. *Agric. Ecosyst. Environ.* 34, 407–419.
- Feller, C., Albrecht, A., Tessier, D., 1996. Aggregation and organic matter storage in kaolinitic and smectitic tropical soils. In: Carter, M.R., Stewart, B.A. (Eds.), *Structure and Organic Matter Storage in Agricultural Soils*. CRC Press, Boca Raton, FL, pp. 309–359.
- Gale, W.J., Cambardella, C.A., Bailey, T.B., 2000. Surface residue- and root-derived carbon in stable and unstable aggregates. *Soil Sci. Soc. Am. J.* 64, 196–201.
- Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P., 1994. Study of free and occluded particulate organic matter in soils by solid-state  $^{13}\text{C}$  NMR spectroscopy and scanning electron microscopy. *Aust. J. Soil Res.* 32, 285–309.
- Golchin, A., Clarke, P., Oades, J.M., Skjemstad, J.O., 1995a. The effects of cultivation on the composition of organic matter and structural stability of soils. *Aust. J. Soil Res.* 33, 975–993.
- Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P., 1995b. Structure and dynamic properties of soil organic matter reflected by  $^{13}\text{C}$  natural abundance, pyrolysis mass spectrometry and solid-state  $^{13}\text{C}$  NMR spectroscopy in density fractions of an Oxisol under forest and pasture. *Aust. J. Soil Res.* 33, 59–76.
- Gregorich, E.G., Janzen, H.H., 1996. Storage of soil carbon in the light fraction and macro organic matter. In: Carter, M.R., Stewart, B.A. (Eds.), *Advances in Soil Science. Structure and Organic Matter Storage in Agricultural Soils*. CRC Press, Boca Raton, FL, pp. 167–190.
- Gregorich, E.G., Monreal, C.M., Schnitzer, M., Schulten, H.R., 1996. Transformation of plant residues into soil organic matter; chemical characterization of plant tissue, isolated soil fraction, and whole soil. *Soil Sci.* 161, 680–693.
- Hassink, J., 1995. Density fractions of soil macroorganic matter and microbial biomass as predictors of C and N mineralization. *Soil Biol. Biochem.* 27, 1099–1108.
- Janzen, H.H., Campbell, C.A., Brandt, S.A., Lafond, G.P., Townley-Smith, L., 1992. Light-fraction organic matter in soils from long-term crop rotations. *Soil Sci. Soc. Am. J.* 56, 1799–1806.

- Jastrow, J.D., 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. *Soil Biol. Biochem.* 28, 665–676.
- Kay, B.D., 1998. Soil structure and organic carbon, a review. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL, pp. 169–197.
- Kelley, G.E., Edwards, W.M., Harrold, L.L., McGuinness, J.L., 1975. *Soils of the North Appalachian Experimental Watershed*. Miscellaneous Publication No. 1296. ARS and SCS-USDA, Washington, DC.
- Kemper, W.D., Rosenau, R., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), *Methods of Soil Analysis*. Part I. Physical and Mineralogical Methods. Soil Science Society of America, Madison, WI, pp. 425–442.
- Magid, J., Gorissen, A., Giller, K.E., 1996. In search of the elusive “active” fraction of soil organic carbon: three size-density fractionation methods for tracing the fate of homogeneously  $^{14}\text{C}$  labeled plant materials. *Soil Biol. Biochem.* 28, 89–99.
- Miller, R.M., Jastrow, J.D., 1990. Hierarchy of root and mycorrhizal fungal interactions with soil aggregation. *Soil Biol. Biochem.* 22, 579–584.
- Oades, J.M., Waters, A.G., 1991. Aggregate hierarchy in soils. *Aust. J. Soil Res.* 29, 815–828.
- SAS Institute and Inc., 2002. *SAS Procedures Guide*, Version 8. 02. SAS Institute Inc., Cary, NJ.
- Six, J., Callewaert, P., Lenders, S., De Gryze, S., Morris, S.J., Gregorich, E.G., Paul, E.A., Paustian, K., 2002. Measuring and understanding carbon storage in afforested soils by physical fractionation. *Soil Sci. Soc. Am. J.* 66, 1981–1987.
- Six, J., Elliot, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *Soil Sci. Soc. Am. J.* 62, 1367–1377.
- Sollins, P., Homman, P., Caldwell, B.A., 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. *Geoderma* 74, 65–105.
- Sollins, P., Glassman, C., Paul, E.A., Swanston, C., Lajtha, K., Heil, J.W., Elliott, E.A., 1999. Soil carbon and nitrogen: pools and fractions. In: Robertson, G.P., Bledsoe, C.S., Coleman, D.C., Sollins, P. (Eds.), *Standard Soil Methods for Long-Term Ecological Research*. Oxford Univ. Press, New York, pp. 89–105.
- Stevenson, F.J., 1994. *Humus Chemistry: Genesis, Composition, Reaction*, 2nd ed. Wiley, New York, p. 496.
- Wander, M.M., Traina, S.J., 1996. Organic matter fractions from organically and conventionally managed soils. 1. Carbon and nitrogen distribution. *Soil Sci. Soc. Am. J.* 60, 1081–1087.
- Whalen, J.K., Bottomley, P.J., Myrold, D.D., 2000. Carbon and nitrogen mineralization from light- and heavy fraction additions to soil. *Soil Biol. Biochem.* 32, 1345–1352.